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Experimental study of the characteristic of frosting on low-temperature air cooler

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ABSTRACT

In order to find out the influencing factors of frosting on air coolers, the experiments were conducted for air coolers under frosting, and the frost layer thicknesses under various operating conditions were measured with the aid of microphotography. Experimental results show that the frosting process for air coolers is significantly influenced by those parameters including the fin spacing, coating material over fin surface, air relative humidity, evaporating temperature and air flow rate. It is found out that the smaller the fin spacing is, the earlier frosting occurs and the faster the frost grows. The frosting can be delayed by coating the hydrophilic material over fin surfaces; however, the frost quantity is not obviously affected. Under the condition of large air relative humidity, the frost growth rate increases, and the increasing tendency drops off when the relative humidity is larger than 80%. The starting time of frosting may not be obviously influenced. The lower the evaporating temperature is, the larger the frost growth rate. As the evaporating temperature decreases, the initial morphology of frost layer varies from large and flat shape to needle-shape or column-shape due to the increasing of temperature difference. The occurrence of the frosting is delayed by increasing the air flow rate and the increasing of frost layer thickness can also be delayed due the melting of frost, but the frosting rate is not sensitive to the air flow rate.

1. Introduction

Air coolers are important applications of heat exchangers, which performance is significantly affected by frost formation [1]. On one hand, frosting increases the thermal resistance and deceases the air mass flow, as a result, the heat transfer coefficient of the air cooler is reduced; on the other hand, the increasing frost lowers the evaporating temperature and the refrigerating capacity, hindering the routine performance of the refrigerating system. Therefore, it is important to search effective methods to restrain the frost formation and use them to improve the performance of heat exchangers which operate under frosting conditions.

In recent years, there are a series of studies on frosting. Some basic studies have been carried out to investigate the frosting formation on the simple-shaped cold surfaces, in which the process and mechanism of the frosting growth [2–6] and the shape transformation of frost [7–11] were mentioned. A few methods were also proposed in order to predict the physical property of the frost [12–14]. Moreover, the frosting characteristic of the finned tube exchanger has been investigated. Experimental studies have been conducted to investigate the frosting of louver finned tube exchangers and it is found out that the air of low flow rate leads to frosting formation, and pressure drop obviously increases with the increasing of relative humidity, additionally, the large fin spacing has no significant effect on the heat exchanger performance [15–17,22]. Some experimental investigations were performed to study the frosting characteristic of the heat exchanger of air source heat pump. The results show that the growth of the frost thickness is sectional, the frost growth rate increase rapidly in late stage of frosting, which was resulted from the shape transformation of the frost. Furthermore, the effects of relative humidity on the frost thickness are greater than that on the frost quantity [18–20].

Frosting is a complicated process of heat and mass transfer, which is closely related to the structure of heat exchanger and the environmental conditions. As the structures of the heat exchangers are quite different for different applications, the results for simple-shaped surfaces can only serve as a reference. The recent research about frosting performance for an air cooler in low-temperature applications is still relatively few, which is the focus of the present study.

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Nomenclature

Roman symbols

a	supersaturation degree
d	diameter, m
G	gibbs free energy, kJ kg^{-1}
H	enthalpy, kJ kg^{-1}
m	mass, kg
n_d	number of tube stages
n_r	number of tube rows
p	pressure, Pa
P_e	evaporating pressure, kPa
P_f	fin spacing, mm
q	latent heat, kJ kg^{-1}
R	gas constant 8.314472, J K^{-1}mol^{-1}
RH	relative humidity, %
S	entropy, kJ kg^{-1}K^{-1}
S_1	tube pitch, mm
S_2	column pitch, mm
T	temperature, K
TD	temperature difference, °C
T_d	air dry-bulb temperature, °C
T_{dew}	dew point temperature, °C
T_e	evaporating temperature, °C
T_w	air wet-bulb temperature, °C
T_2	saturation temperature of pressure P, K
T_3	wall temperature, K
U	thermodynamic energy, kJ kg^{-1}
v	specific volume,m^3 kg^{-1}
V_a	air volume, m^{3}h^{-1}

Greek symbols

ζ	supercooling degree
δ	thickness, mm
ρ	density, kg m^{-3}

Subscripts

s	saturation
fr	frost

The structural parameters of an air cooler include of tube diameter, tube spacing, fin spacing, fin material, etc. The operating parameters consist of dry-bulb temperature, wet-bulb temperature, evaporating temperature, air flow rate, etc. Considering the correlation of each parameter and production processes, in the present study, the effects of the fin spacing, fin coating material, relative humidity and evaporating temperature were investigated on the performance of air coolers during frosting process.

2. Frosting mechanism over cold surface

Frosting on an air cooler surface refers to frost formation of moisture in the air on the surface of finned tube when the temperature of the surface of finned tube is lower than the dew-point temperature of the environment. Besides, when the temperature is below freezing point, the moisture in the air is condensed on the surface, consequently, the frost forms. According to the characteristics of frost layer growth, the frosting process can be divided into three stages [21]; (a) crystal growth period, (b) frost growth period and (c) frost layer full growth period. Frost crystal growth can be divided into two distinct processes: nucleation and crystal growth process. The nucleation process is composed of two stages, namely, the formation of condensation nuclei and droplet grown.

Essentially, the frost formation is phase transition process of water vapor in the air. According to phase transition dynamics, the fundamental reason for phase transition is the existence of driving force between the metastable phase and stable phase, which makes the material change from metastable phase to stable phase [23]. Such driving force is called phase transition driving force. The transition from metastable phase to the stable phase occurs because the Gibbs free energy of the metastable phase is higher than that of stable phase, therefore, the difference of Gibbs free energy in phases is the basic reason for the existence of phase transition driving force.

The Gibbs free energy G is defined as

$$G = U - TS + pv = H - TS, \tag{1}$$

$$dG = -SdT + vdp, \tag{2}$$

where U is internal energy, T is temperature, S is entropy, H is enthalpy.

Fig. 1 is the phase diagram for water, in which point 1 indicates the state for water vapor in the moist air, point 2 is the corresponding saturation state with the same temperature as point 1, point 3 represents the cold surface. The phase transition happens driven by the difference of Gibbs free energy of points 2 and 3. For the simplicity of calculation, the difference of Gibbs free energy is determined by

$$\Delta G = G_2 - G_3 = -\int_2^3 dG = -\int_2^3 (-SdT + vdp) = -\left(\int_2^4 -SdT + \int_4^3 vdp\right). \tag{3}$$

If water vapor is assumed as ideal gas, the specific volume is given as

$$v = \frac{RT}{p}. \tag{4}$$

The entropy at gas state under saturation is calculated by [23]

$$S = 4.1868\ln\frac{T_s}{273.16} + \frac{q}{T_s}. \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (3), the difference of Gibbs energy is given as

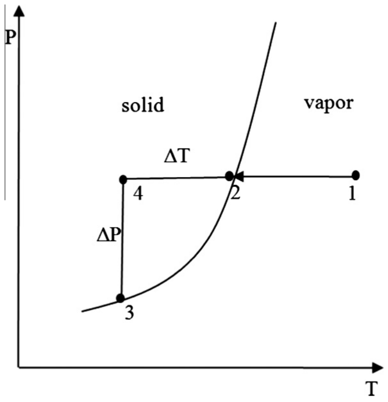

Fig. 1. Phase diagram for water.